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Review Article

Instruments to Measure Thermal Conductivity of Engineering Materials - A Brief Review

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ABSTRACT

Insulation materials are used in various engineering applications for improving energy efficiency and performance. Efficient thermal conductivity is one of the most important factors pertaining to the determination of the efficiency of the system, so it is important to know how the material performs under various conditions in the sense of thermal conductivity and how it can be configured for better results. The aim of this paper is to paper is to identify efficacious apparatus and techniques for determining the thermal conductivity values through steady-state methods and transient methods. The review work presented herein discusses about various apparatus/ methods considered and utilised by various researchers like the guarded hot plate, hot wire, modified hot wire, laser flash diffusivity, and many more, which are based on the principles of heat transfer for the measurement of thermal conductivity of engineering materials is done. These instruments have been found effective for the measurement of thermal conductivities of various materials. Such apparatuses are examined in the sense of their suitability for specific materials, such that it is possible to determine which instrument to be selected in context to the type of material for which the thermal conductivity is to be determined. Laser flash and Guarded Hot Plate apparatus are very frequently used and their use has increased for quite some time.

Keywords: Thermal Conductivity, Radial Heat Flow Method, Guarded Heat Flow Meter, Hot-Wire Method, Laser Flash Method

Introduction

The ability of any material to conduct or transfer the heat is called thermal conductivity; usually, it is denoted by K and λ.[1] Let us understand thermal conduction with an example walking barefoot on bathroom tile in winter your feet feel cold and don't feel cold if you walk on the carpet while both carpet and tile are placed at temperatures as the interior of the house has a temperature. This is because every material transfers heat at a different rate.[2] The tile and stone conduct the heat at a much faster rate than the carpet and fabric. For that reason, in winter you feel cold on tile and stone because heat transfer between your feet are much fast as compared to fabric or carpet.

For the past few years, a method has been practiced to find out the thermal conductivity of any solid and powder solid. Every material has a there fixed range due to that barrier every apparatus is not made for every material there is some limitation for every apparatus vary from material to material which is based on the fundamental laws of heat conduction. For finding the thermal conductivity of any material there are some apparatus In Figure 1, a flow chart is there which will brief you what is next in this paper.

There are two ways by which thermal conductivity namely the Steady-state method and Transient method.

- Steady-state method

Thermal conductivity in the steady-state method is to find out when the temperature of any sample attains equilibrium and also generates a constant signal.[3] Steady-state measurements thermal conductivity is derived by the laws of Fourier's which are based on temperature gradients. The steady-state measurement is further divided into two parts such as comparative methods and absolute methods which is based on a technique from which heat flux can major.[4] comparative methods consist of a sample whose thermal conductivity is known to us and placed in the series with material that has to be tested and from the temperature distribution of reference samples, the heat flux is extracted indirectly from any sample. On the other hand, if we talk about absolute methods, in this heat flux is determined through electrical powder. The sample is heated with a familiar powder by putting it in the heat source.[5]

The steady-state method is further divided into some parts such as the Radial Heat Show Method, Comparative Cut Bar Method, Guarded Heat Flow Meter, Guarded Hot Plate Method and many more which brings into play for finding thermal conductivity of different materials.

- Transient Method

The transition method is a known steady-state measurement technique which has become very popular[6] temperature, and weight fraction on the thermal conductivity ratio of alumina (Al_2O_3). In transient techniques time responsible for the change in temperature and it measures accordingly Heat source supplies heat either in a periodically or in a pulse foam. A further transient method is divided into periodic heat flux and transitional heat flux methods. In transient methods, Hot-wire method, Thermal probe method, transient plane source method, laser flash method, is used to determine thermal conductivity[6] temperature, and weight fraction on the thermal conductivity ratio of alumina (Al_2O_3).

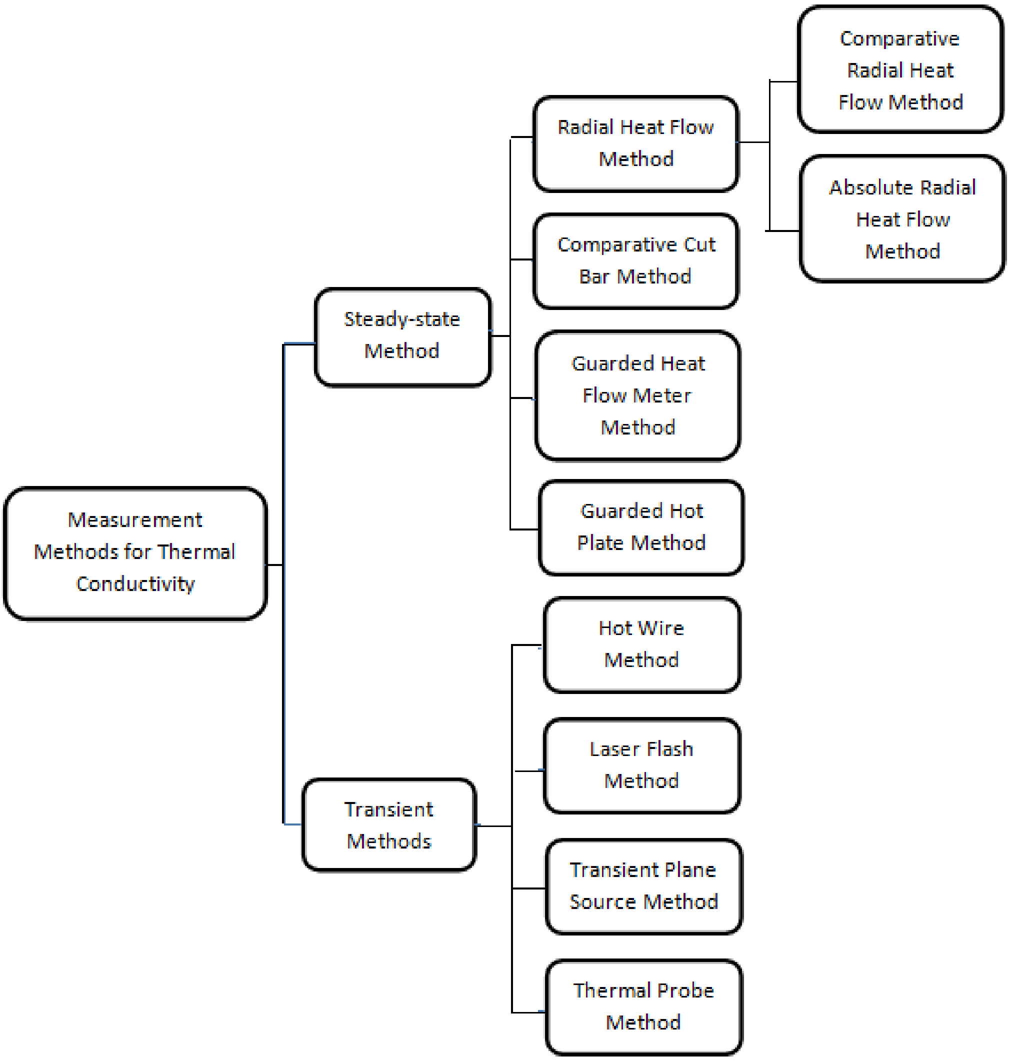

Figure 1.Some methods for measuring thermal conductivity

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Instruments

Steady-state Methods

Radial Heat Flow Method

Radial heat flow should be maintained across the cylinder sample in one dimension on the other side circumcferential heat flow and undesired heat flows should be minimized. Due to ISO 8497, there is a proper testing procedure and has measurement requirements for finding thermal conductivity.[7] In Figure 2a, schematic diagram of the Radial Heat Flow Method used to discover thermal conductivity.

In typical radial flow apparatus, the cylinder heater is placed on top of the cylinder test sample in the central axis and the radial direction steady-state temperature gradient is established. Usually, the temperature difference in the cylinder test sample is around 30 to 60 ^{0}C.[8] Thermal conductivity for one-dimensional radial heat flow can be extracted from the Fourier heat conduction equation for which the heat flux and temperature have to be determined at different known radii.[9]

This apparatus consists of some parts such as a heating coil which is in the central axis of the inner cylinder. This coil is made up of nichrome wire with a coil diameter of 2.5 mm[10] gastric juice and bile salts 0.3%. We also carried out an in vitro evaluation of LAB aflatoxin binding ability in viable and non-viable cell for 24 and 48 hours of incubation. The measurement of aflatoxin content was performed by ELISA method using Agra Quant Total Aflatoxin Assay kit. The results showed that all isolates were potential as probiotics and the G7 isolate had the highest viability among other isolates in pH 3 (92.61%). The material which is needed to be tested is to be sandwiched, in the inner and outer concentric cylinder with High-Density Polyethylene (HDPE) on both sides. HDPE is commonly used because of its ease of the machine, less expensive, and shows good chemical resistance.[11]

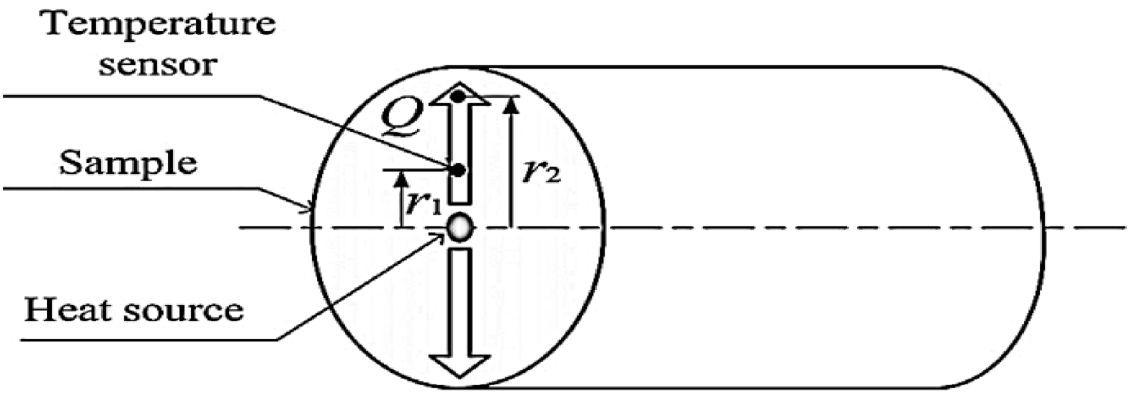

Figure 2.Schematic of the radial heat flow method for determining thermal conductivity

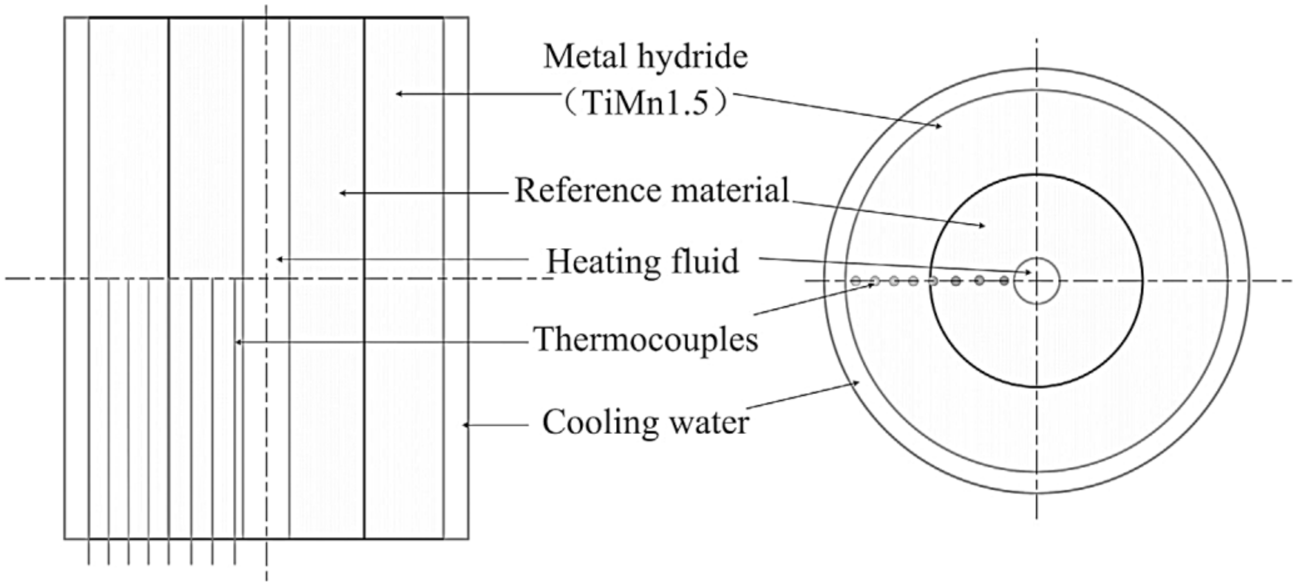

Figure 3.Schematic apparatus based radial heat flow technique

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Table 1.A literature review of Radial heat flow method used for various materials

Author	Year	Material	Findings	Ref. No.
T. G. Godfrey et al.	1965	Polycrystalline, UO_2	The thermal conductivity of polycrystals and UO_2 is on maximum at room temperature and its behavior can also associate with specific heat.	[12]
W. Fulkerson et al.	1964	Uranium dioxide and Armco iron	In this paper, absolute thermal conductivity results show by the radial heat flow Which can assume to be about 1.5% accurate and repeatability, it is 1.5% at a temperature of 100 to 1100°C. For both conductivity semiconductor and high conductivity metal UO_2 and Armco iron reflectively.	[13]
A. B. Donaldson et al.	2008	ARMCO IRON	It has been found that radial heat flow methods are very feasible for finding thermal diffusivity. Experimental has also revealed that the axial heat flow method with a combination of radial heat flow correction exhibits good value but the condition is that whatever constraints are mentioned in this paper follow that honestly.	[14]
A. R. Challone et al.	1958	Pyridine and three Chlorofluorocarbon oils	The paper explains that in the family of liquids chlorofluorocarbon oil has the lowest thermal conductivity.	[9]
J E S Venart et al.	1964	Nitrogen, Carbon Dioxide, Sulphur hexafluoride, carbon tetrachloride, ethyl bromide, ethyl alcohol, toluene, water and water-Pluracol solutions	The earlier experiment shows that the reproductively and accuracy of a fluid as compare to water-Pluracol solutions accuracy is around 2%.	[2]

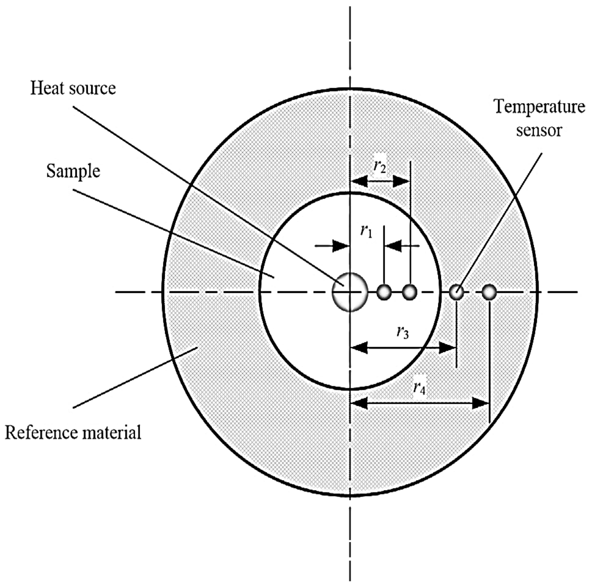

Figure 4.Schematic of the comparative radial heat flow method for determining thermal conductivity

Guarded Hot Plate Apparatus

Guarded Heat Flow Meter method in which the specimen and heat flux transducer are sandwiched between the hot plate and the cold plate so that the heat flow can be generated through the test stack[15] methods and principles for the measurement of the effective thermal conductivity of metal hydride beds are discussed, including steady-state techniques (the radial heat flow, comparative cut bar, guarded heat flow meter, and guarded hot plate methods). The specification should have a diameter of 50.8 (±)0.25 mm, thickness 0.5 – 5.4 mm and its uniformity is 0.025 mm. With the help of a heat flux transducer, the flow of heat of any specimen can measure.[16] When the measured temperature is not changed by more than 1 degree in 1 minute, it means that the thermal equilibrium has been attained and with the help of recording the temperature and output heat flux transducer is achieved. The thermal conductivity and be get by solving the calculation by measuring the temperature from the top and bottom surface of the sample with the help of mathematical formula:[17]

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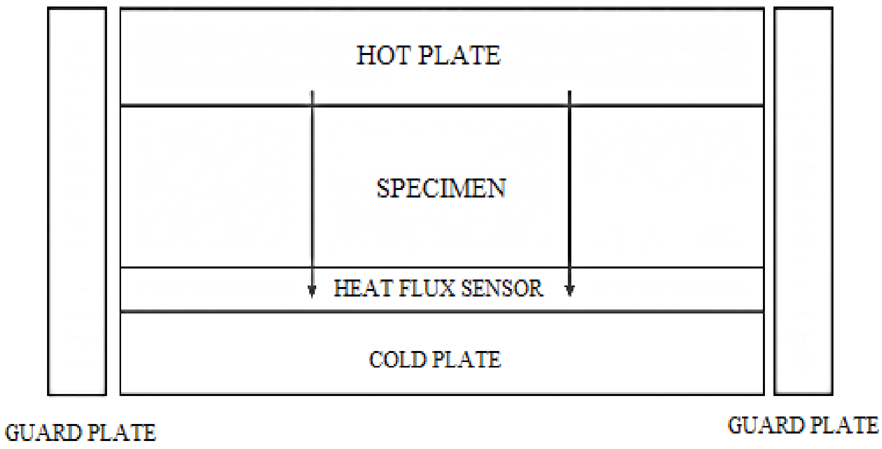

Figure 5.Simplified view of a guarded hot plate apparatus for finding thermal conductivity

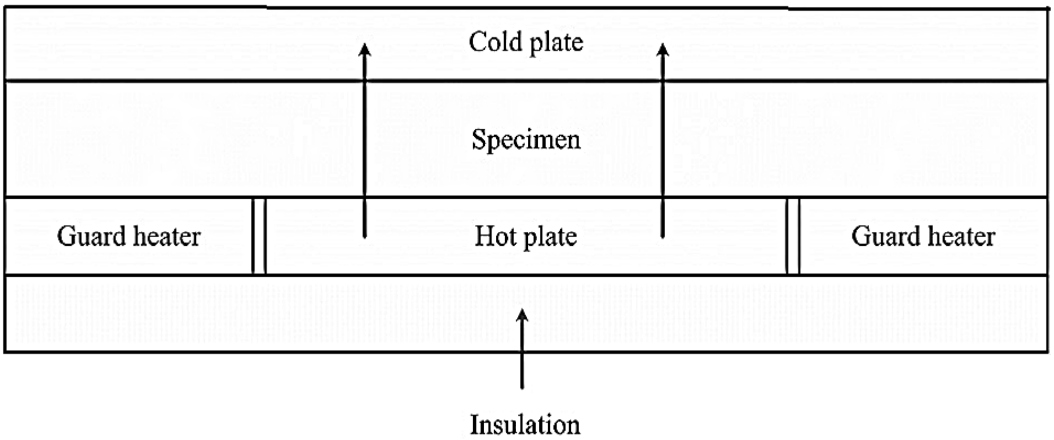

Figure 6.Schematic views of finding thermal conductivity through the guarded heat flow meter method

Table 2.Literature review Guarded Heat Flow Meter Method for various materials

Author	Year	Material	Findings	Ref. No.
U. Hammerschmidt et al.	1995	Polar refrigerant R22; R123; R134a; R142b; R143a; R152a;	The Hotwire technique is usually used as potential electric and chemical interaction between wired and pole refrigerantAnd on the other hand, protected hot plate devices have no such difficulties.	[22]
David Salmon et al.	2001	Insulation material	This review paper shows that still has some scope for improvement, especially in heat transfer in radiation from which measurement of high temperature starts. And it becomes a prime model for some materials.	[23]
William C Thomas et al.	2011	Insulation materials	With the help of mathematical modeling, The thermal performance of the guarded hot plate operator can be controlled.	[24]
Christian Suryono Sanjaya et al.	2011	Pores in the porous materials	Specimens which either have same or different thermal conductivity can also be extracted from the gradient heat flow method.	[25]
M. C. I. Siu et. al.	1998	Insulation material (fibrous glass board)	SRM 1450 Specimenindicates that line heat source and guarded hot plate apparatuses show similar results.	[26]

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The guarded hot plate method can be divide into two parts double specimen and single specimen. Schematic views of finding thermal conductivity through the guarded heat flow meter method for a single specimen is shown in Figure 6. The guarded hot plate method is divided into four parts cold plate, hot plate, guard heaters, and thermal insulation.[18] Around the hot plate, there are guarded heater and thermal insulation to ensure that through this method a high precision can be attained.[19] To make measurements of temperature differences, accurate make sure that there is a difference of 10-20 K between cold and hot plates; it will reduce the chance of getting error. This is a standard method to measure the thermal conductivity of any specimen, especially for the materials which have low thermal conductivity.[7] At last, the biggest disadvantage of this method is that the specimen size should be large, the measuring time is long and the temperature difference between the specimens should be more.

Guarded heat flow meter method is not an absolute method it requires instruments for complex and operational construction.[20] The biggest drawback of this apparatus is that there are no reliable heat transducers to measure high temperatures.[21]

Transient Method

Hot Wire Method

The hot wire method was described by Schieirmader in 1888 but was first used in 1949 by the Van Der Held and Van Drunen and they also find out some of the results through hotwire apparatus, which led to being used to find thermal conductivity and it also tells the thermal conductivity of the strongest acid.[27] There is a procedure of using this apparatus is, the electric current has to be passed for a respective time through a thin wire and the wire has to be placed inside the homogenius material whose thermal conductivity has to know.[28]

The hot wire method that was applied to determine the thermal conductivity of liquid such as alcohol toluene, silicone silicon oil, and many more. What impact it will have on temperature to get further information for that more study is required.[29]

Hot wire method is a standard translate dynamic technique that is based on the temperature measurement in the fixed distance which is from the hot wire which is rooted in the respective test specimen. It seems that the length of the hot wire is infinite, moreover, the diameter is extremely small and has a heat capacity almost non-existent negligible.[30]

This Hot wire technique is further divided into three configurations according to experimental:

- Resistance method
- Crosswire technique
- Parallel wire technique

The resistance method contains one wire on the other hand crosswire and parallel wire contains double the wire used in the resistance method. A platinum wire is usually used in this apparatus because its linear template registration is very good if it is compared with another metal.[31] A key issue for the fabrication of accurate gas sensors, infrared emitters with high spectral purity, and micro-reactors with uniform deposition on sufficiently large areas. Here, by considering a circular heater geometry and typical (i.e. very small. Once the permission granted then the sample has to equilibrate for at least 1 hour, the sample has to be tested by at least three tests for that temperature is decided from ASTM C1113/C1113M-09.[32] The applicability of the GHP apparatus to estimate thermal conductivity of two specimens with different thermal conductivity was investigated. To predict the value of thermal conductivity of two different specimens, a new testing method is proposed using multiple linear regression analysis. In the new testing method, the issue of multicollinearity statistical dependency

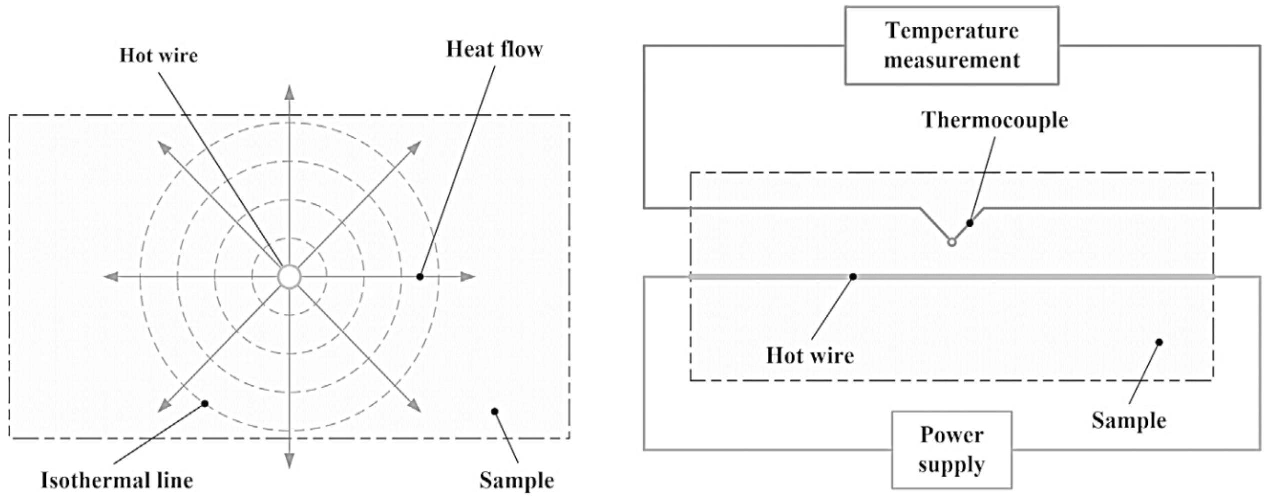

Figure 7.Diagrammatic representation of the hot wire apparatus for finding thermal conductivity

between two predictors. Once all the elevated temperature tests have been done and, then thermal conductivity is calculated by the Fourier equation and that too at the rate at which the temperature in the wire and power input are increased.[33]

The hot wire method for determining the transient thermal conductivity proves to be very effective as it is very quick, not much time consuming and very easy to use. Using this method the thermal conductivity of materials such as solid powder, fluid, nonfluids can be obtained[34] methods and principles for the measurement of the effective thermal conductivity of metal hydride beds are discussed, including steady-state techniques (the radial heat flow, comparative cut bar, guarded heat flow meter and guarded hot plate methods). However, this hot wire method does not apply to so many materials some are anisotropic material, films, sheet samples and materials that have high thermal conductivity.[35]

Ultimately, the accuracy of the hot wire method is not very high, as compared to the steady-state method and it is used very rarely in these commercial places, which is because the hot wire is very thin and very delicate.[36]

Table 3.A literature review on the hot wire method on various materials

Author	Year	Material	Findings	Ref. No.
Wenli Zhao et al.	2020	Metals hybrid beds	In this paper a review on the etc of the metal hydride bed taking reference of various methodology.	[15]
Alessandro Franco et al.	2007	Mortar and lateritic bricks	Through this paper, the experimental thermal conductivity of the building material is point 0.2 and 1.5 w/mK and the accuracy rate is almost 5%.	[37]
Y Nagasaka et al.	1981	Aqueous NaCl Solution	The experiment was conducted in which the thermal conductivity aqueous NaCl solution is tested at 0 to 45^{0}c at atmospheric temperature. The accuracy rate of this measurement method is + and – 0.5%.	[38]
L. Vozár et al.	1996	Crosswire	A modified hot wire apparatus is developed through the which is fully controlled by computer.	[39]
P. Andersson et al	2008	AgCl and polytetrafluoroethylene	An electronic circuit in which constant power is supplied in a nickel wire acts as a resistance thermometer. AgCl and polytetrafluoroethylene thermal conductivity can be major up to 10 kilobars.	[40]

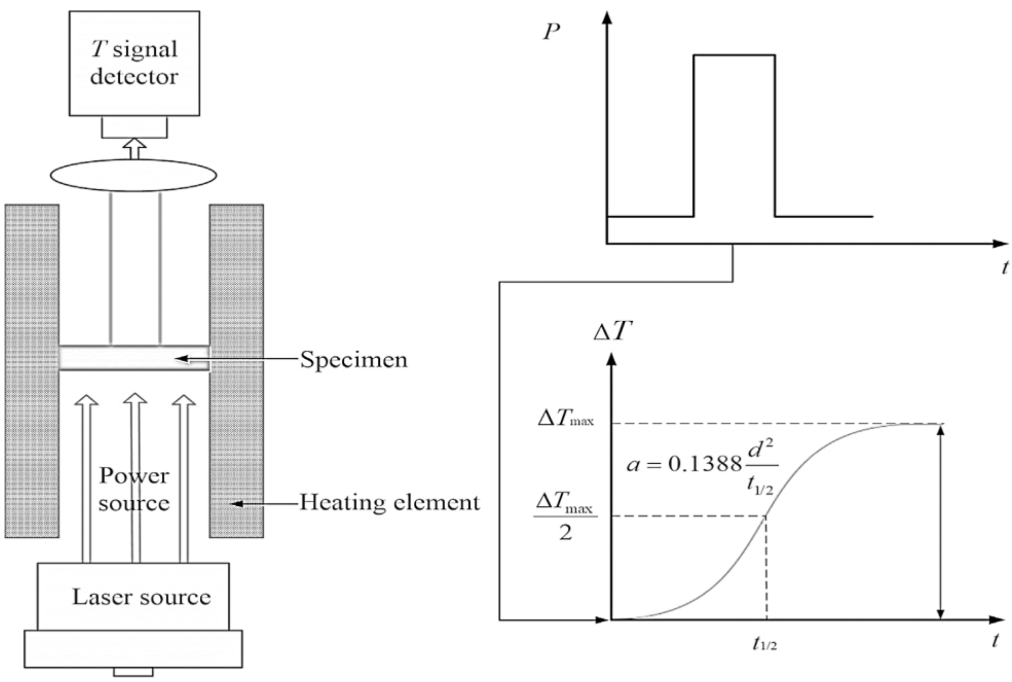

Figure 8.Diagrammatic representation of the laser flash method for finding thermal diffusivity

Table 4.A literature review on the laser flash method on various materials

Author	Year	Material	Findings	Ref. No.
Tetsuya Baba et al.	2001	Glassy carbon	Improvises the method so that thermal diffusivity can be measured above the room temperature.	[44]
H. Mehling et al.	1998	Slide glass of a microscope and a high-grade plate made of fused quartz	In this paperwork is done to find thermal diffusivity of the sample which are made of the nonscattering material.	[45]
B. Hay et al.	2005	Armco iron and pyroceram	Results of the experiment as follows temperature range 20 to 800^{0}C where k=2.	[46]
Tsuyoshi Nishi et al.	2003	Molten iron, cobalt, and nickel	Thermal conductivity of these materials is found by combining the previous data .by that three equations in given.	[47]
T. W. Wojtatowicz et al	1989	St3SX	The results obtained through these two methods is good.	[48]

Laser Flash Method

The laser flash method is a very easily available method for determining thermal conductivity, thermal diffusivity, and specific heat capacity of solid material.[41] In this method, the head of the specimen is placed in the exposure with a short pulse laser light. Because the material is kept in the exposure of the laser light as the time passes the surface which is in the contact to the laser gets heated[42] which leads to a rise in the temperature of the surface which can be monitored with the help of the detector attached with the surface as shown in the Figure 8.

Graphite is sprayed on both sides of the specimen on one surface on which heating laser is to work their graphite will work as an absorber, on the other hand, the back surface of the specimen where the detector is attached here graphite will act as an emitter.[2] This is the reason why graphite is sprayed on the specimen before use. As soon the thickness of the specimen is available, with the help of this thermal diffusibility calculation can be done as the temperature rises as a function on time on the surface behind the sample[43] drying and devolatilization of fuel from processes of gasification and combustion of carbon residue. The choice of process parameters helps control fuel gasification. Addition of the driving gas to the chamber PC1 with specific composition (O_2, CO_2).

Conclusion

In this paper, we have studied different methods by which thermal connectivity finds such as the hot guarded plate method, laser flash method, thermal probe method, transient plane source method, laser flash method. Here we come to know that there are different types of apparatus to measure the thermal conductivity of different materials. These apparatus differ in their design and also and their capabilities for measuring different types of materials. For example, we observe that the guarded hot plate apparatus is usually used for the measurement of the thermal conductivity of solids. In contrast to activated MH materials, we prefer using the laser flash method through the standard procedure to obtain thermal conductivities.[49] The hot wire apparatus is used in the cases or we can say it is preferred in the cases when the material is in form of powder, thus powdered materials are preferred through this device to obtain their thermal conductivity, however, this material is not suitable for anisotropic materials and materials having high thermal conductivity.[50] Thus this paper will serve as a platform for researchers working in the field of heat transfer and thermodynamics in which obtaining the thermal conductivity of metals for composites is needed.

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